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Study on the Numerical Model of 2-Dimensional Surface Flame Spread due to Wind and Slope in Forest Fire

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The characteristics of the spread of a forest fire are generally related to combustibles, geographical features, and metrological conditions such as wind. Analysis of heat energy transmission by the stages is commonly used to create a prediction model. Numerical values in this analysis are generated in each stage when forest fire is developing. With this methodology, the purpose of this study is to develop a 2-dimensinal velocity model of flame spread on surface fire in forest. Variable values were produced in numeric by testing fuel combustion and flame characteristics. An algorithm was developed to be able to perform computational analysis of flame spread via heat transfer analysis of the flame-forms. In this study, algorithm of 2-dimensional flame spread was developed base on heat transfer mechanism in concerning of flame tilt by wind and slope. The experimental and numerically analyzed values for surface fuel beds of *P. densiflora* were compared. The result showed that the mean error rate of their velocities was approximately 12.15%. Thus, the proposed equation and velocity model of 2-dimensional flame spread are expected to be effective in calculating the flame properties and in predicting velocity of surface flame spread.

Keywords: Forest Fire, Numerical Model, Flame Spread Model, 2-Dimension, Surface Fire

Introduction

Forest fire spread can be classified into surface fire, crown fire, spotting fire and ground fire depending on fire type. Surface fire refers to combustion of surface fuel beds such as fallen leaves, twigs, dead fuel and grass. Crown fire refers to entire combustion all the way to treetop. Spotting fire refers to virgin fuel catching fire due to brands transported by the wind. Ground fire refers to combustion of underground organic matters or peat layer. Among these types, surface fire is the most common type of early-stage forest fire, which starts off with horizontal flame spread followed by vertical flame spread to trees' crown layer. Speed of forest fire spread, in general, refers to the flame spread velocity of ground fire and crown fire, of which the speed varies by flame characteristics, combustion characteristics and by the transfer process of heat energy created from flames. Most solid-type fuels emit heat energy through flames, during which the emitted heat flux causes a virgin fuel to go through heat decomposition, temperature rise and eventually ignition when the fuel reaches ignition temperature. Catchpole and De Mestre(1986), Perry(1998) and Weber(1991) revisions of existing surface fire behavior models that are classified as theoretical, empirical and semi-empirical can be found [3][11][15]. The characteristics of the spread of a forest fire are affected by geographical features, meteorological features (wind velocity, wind direction, relative humidity, etc.) fuel (fuel type, fuel humidity, heat emission energy, etc.) and other conditions concerning surrounding forest fire environment.

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The following four considerations should be given to develop forest fire spread model applicable to real forest fires.

Nomenclature

A	coefficient	U	wind
A_i	heat source	x, y, z	axis
A_j	target cell or area from flame	**Greek letters**	
c_p	the specific heat of air at constant pressure (kJ/kg·K)	φ	flame tilt
g	gravity acceleration (m/s^2)	θ	angle
F_{ij}	view factor	**Superscripts**	
H_f	flame height(m)	$'$	line unit (m)
R	the distance between two area(m)	$''$	area unit (m^2)
L_f	flame length(m)	**Subscripts**	
T	temperature (^{o}C)	i	heat source point
Q, q	heat flux(kW)	j	target cell point
ρ_0	the air density (kg/m^3)	s	slope
Z	the characteristic length scale	w	wind

First, fixed factors as topographical factors (slope, surface direction, height) and fuel factors (species of trees and fuel distribution) that affect forest fires and variable factors such as meteorological conditions that vary with time. Second, physicochemical changes witnessed in general fire spread and experimental/theoretical considerations on the correlations between geographical (surface direction, slope) – meteorological conditions (wind velocity, wind direction) and meteorological (relative humidity) – fuel (fuel humidity). Third, development of forest fire spread prediction algorithm by analyzing governing equation and experimental values of variables having relevance with forest fire spread. Finally, development of a program that can display on GIS predicted value obtained through numerical arithmetic processing. These series of processes are being constantly studied all over the world. Forest Fire Research Center at US Forest Service under Department of Agriculture has done a lot of practical research over the past few decades to predict flame spread of forest fire. Most commonly used models assume the correlation of the spread velocity and others related factors obtained from experiments and observations to predict the spread of forest fire. US' BehavePlus and FARSITE, Canada's Forest Service Fire Behavior Prediction System, Australia's Mk 4 MacArthur Fire Danger Meters and CSIRO Grassland Fire Spread Meter, among others, suggested that a spread prediction model assuming wind velocity, slope, humidity and fuel characteristics can serve as predictors for forest fire spread.

However, by excluding how fuel and meteorological conditions work together to determine the course of fire, Hirich and Nobel et al. presented an estimated equation of forest fire spread based on the outdoor experiment values while Albini and Rothermel used flame spread obtained in an indoor experiment. Among these, the widely known forest fire spread prediction programs by BehavePlus and FARSITE use semi-empirical techniques as the basis. Non-physical models, which are based on empirical indoor experiments with external environmental conditions, are designed to easily predict forest fire spread and make a quick application. The absence of analysis on internal/external heat flow and gas flow field change raises questions on the accuracy of predictions analyses, which is one of the areas where overseas forest fire researchers from US, France, Portugal and Greece, to name a few, are working on.

Flame spread takes such a series of process and the same goes for forest fire spread where flames created by such combustibles as fallen leaves, branches and trees spread under radiant and conductive heat transfer mechanism, which are affected by wind and topographical slope. Hence, this study carried out by performing numerical analysis; developing an algorithm capable of performing computational analysis of flame spread via heat transfer analysis of the flame formed.

2-Dimensional Flame Spread Velocity Model

The most common methodology used to create a prediction model for the spread of forest fires, is an analysis of heat energy transfer according to the stage of fire. When a forest fire breaks out, the spread velocity of flame movement can be modeled through physical and chemical analyses of flame formation and heat transfer to its targets at every stage of the fire development. In this study, a formula used for the 2-D surface forest fire behavior prediction model, derived from a numerical analysis of the surface flame spread velocity of solid combustibles, is introduced. Experimental and theoretical equations on flame duration, flame height, flame temperature, ignition temperature of surface fuels, etc., have been applied to derive of this formula.

Configuration of 2-D Flame Spread

The research executed numerical analysis on heat transfer from flame based on the result of combustion experiment on fallen leaves, which are surface combustibles, to develop 2-D surface flame spread prediction algorithm. In general, flame spread velocity of forest fire is mostly controlled by radiant heat transfer and convection heat, which are affected by wind and topographical slope. Majority of forest fuels are composed of porous fuel layer deposited on the upper part alongside soil level surface. Accordingly, the flame spread of forest fires is analyzed with surface flame spread analysis of solid combustibles as shown in Fig. 1. In other words, flame spread can be analyzed with an equation to produce heat energy that heats non-combustibles, whose initial temperature is T_∞, into T_{ig}, the ignition temperature, via heat transmission ahead of front flame.

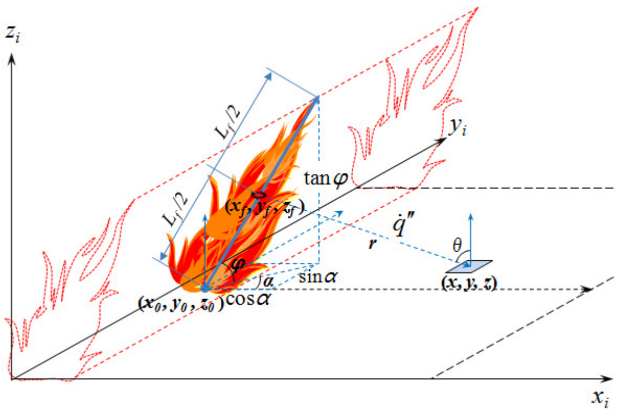

Fig. 1 Schematic of heat flux of the 2-D flame spread.

The schematic in Fig. 1 is the section view of an infinite surface flame that spreads over a fuel bed with thickness δ. The fuel bed is divided into finite segment(or target cell) with uniform physical properties. A segment receives radiative heat from the flame and conductive heat from adjacent segment. The heat transferred to a segment raises the temperature of the segment and vaporizes the moisture contained in the segment. A segment where temperature reached the ignition temperature starts to burn. The flame is formed on the burning segment and the length of the flame is determined by the total heat release rate of the burning segments. The flame on a segment vanishes when the fuel of the segment is consumed.

Stage of Burning of Forest Segment

For analyzing fuel segment burning, the following 5 stages for each segment were considered.

- Stage (1) Temperature rise with moisture
  The fuel bed segment contains moisture and the temperature of the segment rises together with the moisture.
- Stage (2) Vaporization of moisture
  Moisture vaporizes in proportion to net heat gain. The temperature of the fuel bed segment remains to be constant at 100 ^{o}C until the moisture vaporization has completed.
- Stage (3) Temperature rise without moisture
  The fuel bed segment no longer contains moisture. The temperature of the dried segment rises.
- Stage (4) Flaming
  The fuel bed segment burns with forming flames until the fuel has been consumed. The temperature of the segment remains to be constant at flame temperature, T_{flame}.
- Stage (5) Burnout
  The fuel of the bed has been consumed so the fuel bed no more exists.

Mathematical Formulation of Model

This part deals with the mathematical formulation of the 2-D fire spread model, which consists of the formulation of burning and temperature rise of fuel segment, heat transfer to the target fuel segment and flame properties.

① View Factor Model

Heat flux coming out of the flame can be estimated by applying view factor to flame's heat energy. View factor reflects the geometric relationship between heat source, which has a geometric shape, and the area drawing radiant energy from discrete directions. Assessment in this section uses the general expression for the view factors (F_{ij}) of Fig. 2. The view factor (F_{ij}) is defined as the fraction of the radiation, diffusively distributed which comes from the surface with area A_i and goes to another surface with area A_j. For the two infinitesimal surface dA_i and dA_j, the view factor F_{ij} is given by:

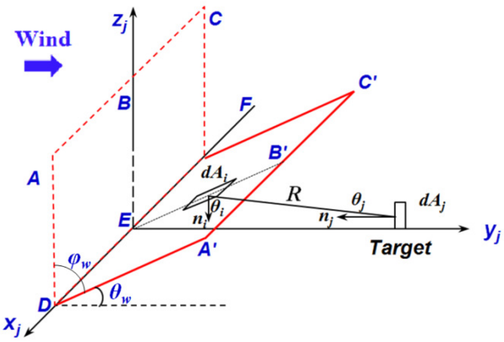

Fig. 2 Simplified view factor geometry between flame front surface and elementary temple structure.

$$dF_{ij} = \frac{\cos\theta_i \cos\theta_j}{\pi R^2} dA_j \tag{1}$$

where θ_i and θ_j are the angles between the unit normal to the areas and the line R represents the distance between two areas and the cosine θ_i and θ_j are given by Eq.(3). Since heat source (A_i) and the target (A_j) are both finite in this case, view factor (F_{ij}) on radiation flux from surface A_i to A_j is simplified as shown in Eq.(2).

$$F_{ij} = \frac{1}{A_1}\int_{A_1}\int_{A_2} \frac{\cos\theta_i \cos\theta_j}{\pi R^2}\, dA_1\, dA_j \tag{2}$$

where R is given by Eq.(3).

$$\cos\theta_i = \frac{l_i(x_j - x_i) + m_i(y_j - y_i) + n_i(z_j - z_i)}{R},\quad \cos\theta_j = \frac{l_j(x_i - x_j) + m_j(y_i - y_j) + n_j(z_i - z_j)}{R} \tag{3}$$

$$R = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2} \tag{4}$$

② Flame length

A numerical analysis of flame length is carried out using an equation as shown by Eq.(3)-(5), derived by Quintiere and Grove (1998), to estimate the flame height of line fire that erupts from combustibles of a surface fire [12]. Quintiere and Grove (1998) plotted experimental data from many existing tests for the height of line fire flame vs. the dimensionless flame ratio z/Z^{**} (used in Eq.5, 6) [12].

$$Z_f = \frac{z}{Z^{**}} = 3 \tag{5}$$

$$Z^{**} = \left(\frac{\dot{Q}'}{\rho_0 c_p T_0 \sqrt{g}}\right)^{2/3} \tag{6}$$

Therefore, Flame length estimation Eq.(7) can be arranged using Eq.(5) and (6). Substituting ρ_0 and T_0 values of 1.2045 kg/m^3 and 293 K in Eq.(6), the former value which is the standard air density and a typical room temperature, the flame height of line fire is estimated as shown in Eq.(7).

$$L_f = 3.0\left(\frac{\dot{Q}'}{\rho_\infty c_p T_\infty g^{1/2}}\right)^{2/3} = 0.027\dot{Q}'^{2/3} \tag{7}$$

③ Flame Tilt due to Wind and Slope

According to Albini, Putnam etc., flame tilt angle of wind-brown flame can be deduced as in Eq.(8) from the relation between the Froude number (Fr) and the wind speed under a uniform wind.

$$\varphi \propto \tan^{-1}\left(A\frac{U_\infty}{\sqrt{gH_f}}\right) = \tan^{-1}(A \times Fr) \tag{9}$$

where, the flame height H_f which is different flame length L_f, is expressed as a function of the flame tilt angle φ_s as

$$H_f = L_f \cos\varphi \tag{10}$$

It can be arranged Eq.(10), using Eq.(9) into Eq.(8).

$$\tan\varphi_w \sin\varphi_w = A\frac{U_\infty^2}{gL_f} \tag{11}$$

where, $\tan\varphi \sin\varphi = \frac{\tan^2\varphi}{\sqrt{1+\tan^2\varphi}}$ from

$$\sin\varphi = \frac{\sin\varphi}{\sqrt{\sin^2\varphi + \cos^2\varphi}} = \frac{\tan\varphi}{\sqrt{1+\tan^2\varphi}}.$$

Hence, flame tilt equation can be rearranged as Eq.(12).

$$\tan\varphi_{ws} \sin\varphi_w s = 1..2\frac{U_\infty^2 + U_s^2}{gL_f} \tag{12}$$

where, the coefficient A in Eq.(12) was proposed A=1.2 [6].

Computational Procedure

The Major variable values and relation equations for flame behaviors required to predict flame spread velocity by testing and making numerical analysis of heat transfer process conducted and radiated by the flame formed are suggested in this research.

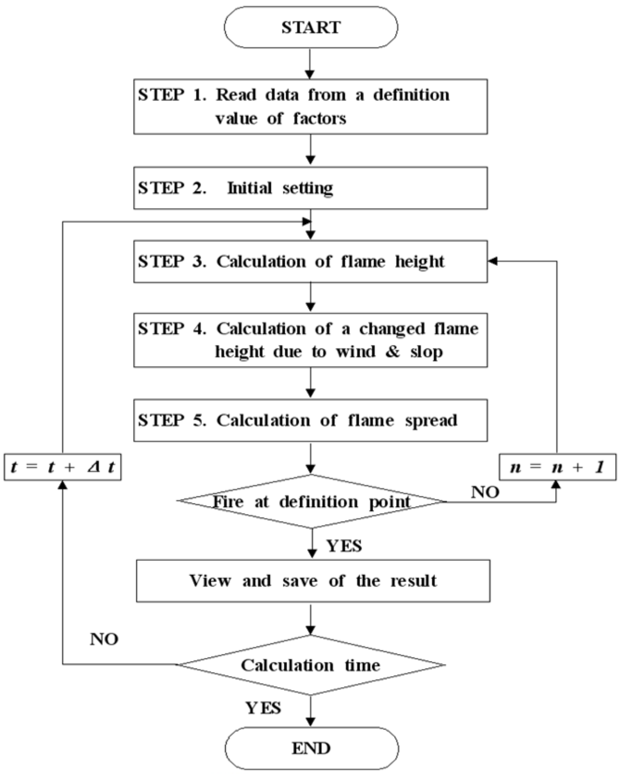

Fig. 3 The main flowchart of calculation for line flame spread velocity prediction

The equations suggested accordingly are put into a flowchart for computational numerical analysis. Initial data entered set fuel's density, wind velocity, slope, initial temperature measured in the test and site survey, and such conditions as the size of grid to be analyzed, the number of grid and computation time. For analysis of a flame formation in fuel segment, it is heated until it reaches 100 °C, at which fuel's moisture evaporates, and once it is there, temperature variation via heat transfer is repeatedly computed until fuel segment reaches ignition temperature. Once computation according to the distance (number of grid) or time defined in the initial setting is over, the time taken for the flame in the epicenter to reach the final grid is computed to obtain flame spread velocity value. The surface fire to reach any point of time that a unit needs 1 sec to yield calculation that describes the program.

The main flowchart for calculating flame spread rate is shown in Fig. 3. Fig. 3 has 5 steps: 1st step to read a necessary data from a measured data and definition value of factors, 2nd step as the initial setting for coordinating firing range of advanced computation as a size of cell, cell number and calculation time, etc., 3rd step as flame height calculation, 4th step as calculation of flame tilt due to slop and wind, 5th step is the step for calculating flame spread model using by a radiative and a conductive heat transfer mechanism.

Result and Discussion

Result of 2-Dimensional Heat Flux

Fig. 4 shows an example for the graph of heat flux in 2-dimensional target cells when flame arrived at *x*-axis and *y*-axis under no-wind and flat condition. As distance from flame recede, the value of heat flux became gradually decrease. Heat flux was shown the highest value at the central part of flame. Hence, flame spread velocity begins to move faster from the central part of flame. These results of heat flux are used in fuel temperature and ignition.

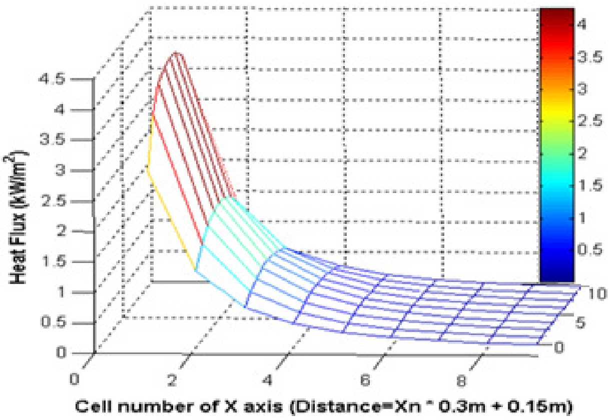

Fig. 4 The value of heat flux by distance under no-wind and flat conditions.

Comparison of Experiment and Numerical Model

Fig. 5 shows comparison of experimental flame spread velocities given by Kim(2010)[6] vs. Proposed 2-Demensional flame spread velocity model results for *P. densiflora* surface fuel beds. Here, an average error between experimental data and predict results is 1.11 cm and average errors have a differential result such as Table 2. Average errors for wind speed condition are 0.17 cm when wind speed is below 1 m/s wind condition and 1.06 cm when wind speed is from 2 to 3 m/s. Average errors for slope gradient condition are 0.83 cm when slope gradient (β) is below 10° and 1.4 cm when slope gradient is 20° to 30°. Hence it was shown more sensitivity in wind speed than slope gradient but it can be predicted for forest surface flame spread velocity with error rate of maximum 12.15%.

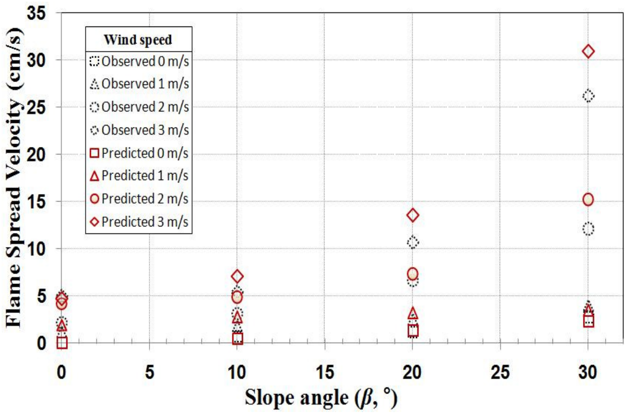

Fig. 5 Comparison of experimental flame spread velocity vs. proposed 2-dimensional flame spread velocity model result for *P. densiflora* surface fuel bed.

Table 2 An average error between experiment data and predicted results for flame spread velocity

Statistics analysis	Ave. errors (cm/s)					Ave. error rate (%)
	Total	Wind (m/s)		Slope (β, °)		
		≤ 1	≥ 2	≤10	≥ 20	
Value	1.11	0.17	2.06	0.83	1.40	13±2

Conclusion

A 2-dimesional flame spread model and program are developed for surface fire spread in forest fires base on heat transfer mechanism with the above research results. The comparison between experimental values and numerically analyzed values for *P. densiflora* surface fuel beds found that predicted flame spread velocity has an average error of approximately 12.15%. Thus, the proposed equation and 2-diemnsional flame spread velocity model are expected to be effective in calculating the flame properties and in predicting surface flame spread velocity. The results attained in this study will be beneficial in the successive students for developing 3-D numerical forest fire spread prediction model.

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